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MICROEARTHQUAKE SURVEY OF THE RADIUM SPRINGS KGRA, SOUTH-CENTRAL NEW MEXICO

Bob Quillin and Jim Combs

MICROGEOPHYSICS CORP.
GOLDEN, COLORADO

GEOTHERMAL SERVICES, INC.
SAN DIEGO, CALIFORNIA

ABSTRACT

For a nine-week period during September, October and November of 1975, seismicity was monitored in the area of Radium Springs Known Geothermal Resources Area (KGRA) located in South-central New Mexico in the Rio Grande Rift. The seismic array consisted of five, three-component seismograph stations with maximum station separation of less than 15 km. Two microearthquakes with coda-duration magnitudes of 0.0 were located and are apparently associated with surface mapped faults in the near proximity of the hot springs. By far the most abundant type of local seismic activity, hundreds of events per day, were nanoearthquakes of from 0.25 to 2.0 sec total duration corresponding to coda magnitudes of -3.2 to -1.1. These nanoearthquakes are caused by natural hydrofracturing associated with the local geothermal regime.

INTRODUCTION

The seismicity of any particular geographic region may have as its source a variety of wave generating phenomena, some of which are of geological origin and are therefore geophysically interesting. Other man-made sources such as well pumps, trains (Sanford et al., 1968), mine blasts, etc., may be scrutinized and discarded if they do not provide useful information. Of the sources which are of geological origin, there are still several mechanisms which may be associated with particular types of earthquakes. For example, large earthquakes, i.e., magnitude (M) $\geq$ 4.0, may be typically associated with active regional tectonics or perhaps violent volcanic activity (Dibble, 1969). As noted by Ward (1972), microeathquakes (M < 3) have been observed near many major geothermal areas around the world. Ward and Björnsson (1971) have shown that geothermal areas which are structurally related to fissure systems generally have microearthquake activity, whereas those areas that have few prominent fissures and seem only related to intrusions of silicic magma appear to have little or no microearthquake activity.

However, there are events, here termed nanoearthquakes (Combs and Hadley, 1977), which may be associated with both types of geothermal areas. Thermally induced differential expansion between fluid in isolated pores and enclosing minerals decreases effective pressure at the pore-mineral interface. With a sufficient increase in temperature, effective pressure becomes equal to the tensile strength, and the rock fractures. This type of mechanism is known as hydraulic fracturing and is inevitable in hot intrusive environments (Knapp and Knight, 1977). The number of events per day produced by this mechanism is a function of the size and age of the intrusion.

Other mechanisms for the generation of nanoearthquakes may be pore pressure in conjuction with local tectonic stress patterns. These nanoearthquakes are important in geothermal areas because they indicate potential free-circulation for geothermal fluids (Brown and Butler, 1977).

The objective of this microearthquake survey at the Radium Springs KGRA was to determine active fault zones in the area and their characteristics by the analysis of the associated seismicity.

GEOLOGICAL, GEOCHEMICAL, AND GEOPHYSICAL BACKGROUND OF THE RADIUM SPRINGS KGRA AND VICINITY

The Radium Springs KGRA is located in the Southern Rio Grande Rift in South-central New Mexico. The Rift is characterized by heat flow values $\geq$ 2.0 HFU (Reiter et al., 1975).

Radium Springs is located at the northern end of the Mesilla Basin (Fig.1), one of the southernmost grabens comprising the Rio Grande Rift (Seager, 1975). The springs issue at the base of a rhyolitic hill on the east boarder of the Rio Grande River lowland with reported temperatures of 76°C and 85°C (Summers,1965). Tests using the Na-K-Ca geothermometer indicated subsurface temperatures in excess of 200°C both at Radium Springs and at a nearby well (Fig. 1; Swanberg, 1975).

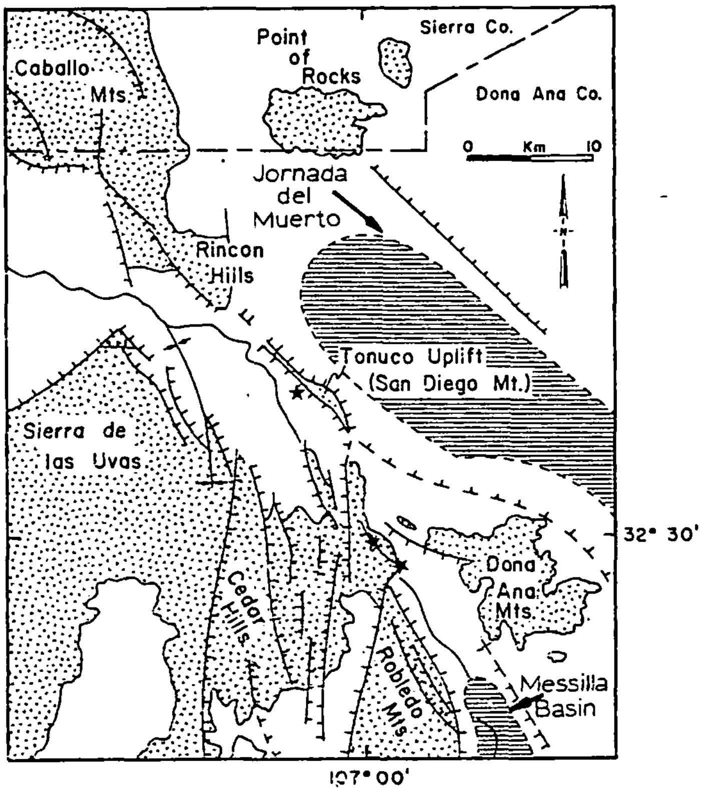

Fig. 1 Late Tertiary fault pattern in Radium Springs vicinity (Seager, 1975). Stars indicate locations of geothermometer temperatures in excess of 200°C (Swanberg, 1975) with middle one indicating Radium Springs while the other two are local water wells.

In one of the few published geophysical studies of the Radium Springs vicinity, Jiracek and Smith (1976) conducted a bipole-dipole resistivity survey covering an area of approximately 65 km^2 of the Southern Jornada del Muerto and Northern Mesilla Valley. This resistivity survey demonstrated that the Jornada del Muerto is structurally separated from the upper Mesilla Valley. However, the questions of the location of the subsurface reservoir for the thermal fluids and the associated heat source were not answered.

In a regional instrumental study, Sanford (1965) located two microearthquakes with magnitudes (M) of 2.8 and 2.9 approximately 7 km southwest of the Radium Springs KGRA. Another microearthquake (M = 2.9) was located approximately 15 km southwest of the KGRA. However, occurrences of geothermal resources are typically charaterized by a relatively high level of microearthquake activity. Assuming that perhaps events of smaller magnitude had possibly gone undetected, a five-station seismic array was deployed in the immediate vicinity of Radium Springs in order to further examine the geophysical characteristics of the Radium Springs geothermal area.

RECORDED SEISMICITY

Events coming from outside the array included events with S-P time intervals ranging from 3.0 to 8.0 sec, which correspond to epicentral

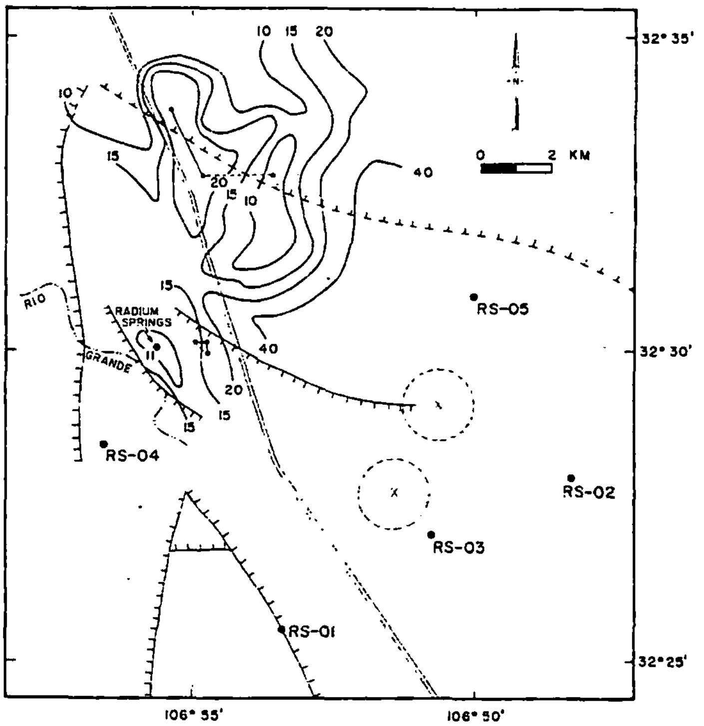

Fig. 2 Multi-information figure. Resistivity contour map of Jiracek and Smith (1976) in ohm-meters. Mapped and postulated faults of Seager (1975). Seismic station locations. Microearthquake epicenters with dashed circles indicating 1 km uncertainty.

distances of about 20 to 60 km, respectively. These events are probably associated with faulting or mine blasts in the San Diego and Caballo Mountains. Only the records of Sept. 29, 30 and Oct. 3 were examined in detail. Two miroearthquakes were located inside the seismic array. Using a layered crustral velocity model and the hypocentral location program HYPO71 (Lee and Lahr, 1975), epicenters were determined to approximately 1 km. The hypocentral locations (Fig. 2) of the microearthquakes are in close proximity to the stations registering the highest level of natural seismicity (RS-02 and RS-05) and appear to be on extensions of mapped or inferred faults. These microearthquakes have coda-duration magnitudes of approximately zero. Microearthquakes of this sort indicate active faulting which could provide permeable paths for fluid convection upward along the fault zone.

By far the most abundant type of events were nanoearthquakes from 0.25 to 2.0 sec total duration equivalent to coda-duration magnitudes of -3.2 to -1.1. Many of these events were obscured by low frequency noise of only slightly lower amplitude. By using a digital bandpass filter (20 to 40 Hz), the high frequency events could be separated from the lower frequency noise.

Another type of seismicity which was recorded were spiky sequences (Fig. 3) which typically lasted from a few minutes to almost 30 minutes. The events were only identified on station RS-05. Each pulse would typically be from one to three cycles in duration, with varying amplitudes. The predominant frequencies of these events were 25 to 40 Hz. Sequences of this type have been recorded and analyzed by Rinehart (1965; 1969) and Nicholls and Rinehart (1967) in a geophysical study of geyser action in Yellowstone National Park. They correlate these sequences with percolation of steam in underground fractures or cavities in the process of heating water which then erupts from the geyser.

With a sufficient increase in temperature, effective pore pressure becomes equal to the tensile strength, and the rock fractures (Knapp and Knight, 1977). In areas of unusually high geothermal gradients these thermally induced events may be generated at much shallower depths, and accordingly in rocks of lower tensile strengths. These induced events would be of very low magnitude and probably occur in swarm sequences such as the events described above.

SUMMARY

The seismicity of the Radium Springs KGRA, located in South-central New Mexico, has been studied using a maximum station separation less than 15 km. Several events per day were detected with S-P time intervals ranging from 3.0 to 8.0 sec, corresponding to epicentral distances of about 20 to 60 km. By far the most abundant types of seismic activity are nanoearthquakes of from 0.25 to 2.0 sec total duration, equivalent to coda magnitudes of -3.2 to -1.1. These nanoearthquakes are caused by natural hydrofracturing associated with the local geothermal regime. The highest numbers of these events were detected on stations

Fig. 3 Spiky Event Sequences

RS-02 and RS-05 (Fig. 2). Two microearthquakes of coda derived magnitude 0.0 were located in the near proximity of seismic stations RS-02 and RS-05 and appear to be associated with extensions of mapped faults (Fig. 2).

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SEISMIC WAVE ATTENUATION ANOMALIES IN THE EAST MESA GEOTHERMAL FIELD, IMPERIAL VALLEY, CALIFORNIA: PRELIMINARY RESULTS

Jim Combs and Dave Jarzabek

GeoThermal Services, Inc.
10072 Willow Creek Road
San Diego, California 92131

ABSTRACT

Seismic wave attenuation anomalies are known to be associated with geothermal areas. Data have been analyzed from calibration blasts detonated within the East Mesa Geothermal Field and from six events of the Brawley earthquake swarm of January, 1975, recorded at portable seismic stations deployed in the vicinity of the geothermal field. Alignment of two or more stations of the array with particular epicenters facilitated the removal of source characteristics. Spectral analyses of these calibration shots and earthquake generated seismic waves have shown anomalous attenuation of high frequency P waves along certain ray paths. The results suggest that the source of the heat anomaly responsible for the East Mesa Geothermal Field is located at depths greater than two kilometers and has a lateral extent of several kilometers.

INTRODUCTION

Increased subsurface temperatures in the vicinity of active volcanoes and geothermal areas are known to cause seismic wave travel time and attenuation anomalies (e.g., Kubota and Berg, 1967; Matumoto, 1971; Combs and Jarzabek, 1977). These anomalies have been interpreted to estimate the volume of anomalous hot rock as well as serve as an exploration tool for delineating potential geothermal reservoirs. Based on the absence of the propagation of S waves and strong attenuation of high frequency P waves along specific ray paths crossing the volcanic range, Matumoto (1971) proposed the existence of one deep (about 20 to 30 km) and three shallow (less than 10 km) magma chambers in the vicinity of Mount Katmai, Alaska. Combs and Jarzabek (1977) observed relative P-wave delays and strong attenuation of higher frequency P and S waves for ray paths which passed through the zone of high heat flow associated with the Coso Geothermal Area, California, and inferred the existence of an extensive body of low velocity material at depth, possibly a magma chamber.

Experimental data on the effects of temperature on seismic wave attenuation are scarce; however, an increase in attenuation with increasing temperature would be intuitively expected. In reviewing previous work of various investigators, Knopoff (1964) concluded that the specific attenuation factor $1/Q$ is independent of frequency for experiments on dry rocks at temperatures and pressures simulating shallow depths in the crust, whereas, the specific attenuation in liquids varies as the first power of frequency. Born (1941) demonstrated that attenuation due to the interstitial fluid is dominant over attenuation in the dry porous rocks even for small amounts of fluid. This observation implies that in a zone of fluid-saturated porous rocks at high temperatures, even when the amount of liquid is small, attenuation will increase more rapidly with frequency than if no liquid is present.

TECTONIC BACKGROUND

The Imperial Valley of Southern California (Fig. 1), within which the East Mesa Geothermal Field is located, is an extensive sedimentary basin characterized by high heat flow (Helgeson, 1968; Combs and Swanberg, 1978). The general geological setting of this area has been described by Dibblee (1954). Structurally the Imperial Valley is controlled by numerous strike-slip faults of the San Andreas--San Jacinto fault systems along which considerable right-lateral movement has occurred (Sharp, 1967). Some of these faults have been active in historic times (Allen and others, 1965; Brune and Allen, 1967; Hill and others, 1975).

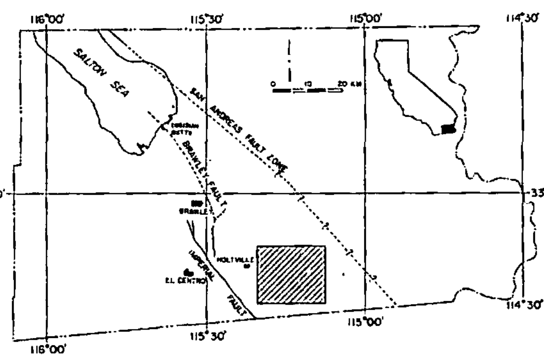

Figure 1. Location map of the Imperial Valley southern California. The East Mesa Geothermal Field is located in the lined rectangle.

The location of the East Mesa Geothermal Field with respect to the major geological faults in the Imperial Valley is shown in Figure 1. Based on seismic refraction profiling, Kovach and others (1962) estimated the depth of the local basement to be at least 4 km. Three wildcat oil wells drilled to depths of 2.44, 3.24, and 3.75 km exist in the immediate area of the East Mesa Geothermal Field. A 1.98 km deep exploratory well, Magma Sharp No. 1, has been drilled west of the field. All of these wells penetrated predominately deltaic sediments and none reached basement. Electric logs from these wells indicate water-saturated interbedded sand and clay with minor silt beds. Five geothermal wells drilled in the East Mesa Geothermal Field indicate the same subsurface geology with the total mass of the upper stratigraphic sequence consisting of more than fifty percent clay which functions as a cap rock for the geothermal reservoir.

The catalog of earthquakes prepared by the California Institute of Technology (Caltech) for earthquakes in southern California from 1932 through 1972 shows a dense pattern of earthquakes with magnitude ≥ 3 within the Imperial Valley (Hileman and others, 1973). During the period 1961 to 1971, three earthquakes of approximate magnitude 3 occurred in the immediate vicinity of the East Mesa Geothermal Field. In view of the tectonic activity and geothermal resource potential, a network of sixteen seismic stations was installed in the Imperial Valley in April 1973 as a cooperative effort between Caltech and the United States Geological Survey (Hill and others, 1975). In 1973 and 1975, this dense seismograph network recorded a series of earthquake swarms along the Imperial and Brawley Faults and a diffuse pattern of earthquakes along the San Jacinto Fault (Hill and others, 1975; Johnson and Hadley, 1976). From examination of these seismograms, the seismicity pattern establishes that slip is presently occurring along both the Imperial-Brawley and San Jacinto Fault systems. Combs and Hadley (1977) analyzed data from the 1973 earthquake swarms and inferred the existence of the Mesa Fault which may function as a conduit for the emplacement of high temperature geothermal fluids in the shallow subsurface beneath the East Mesa Geothermal Field.

RESULTS AND DISCUSSION

To investigate the local subsurface structure and physical properties within the East Mesa Geothermal Field, six calibration shots were detonated on June 3, 1975 and recorded by an array of nine, portable, short-period, high-gain, three-component, magnetic tape recording seismographs (Fig. 2). Each of three shot points had a 14 kg (#2, #4, and #6) and a 68 kg (#1, #3, and #5) explosive.

Spectral analyses of these calibration shots have been carried out in order to examine any attenuation characteristics that may be associated with the temperature anomaly. Time segments of the P phase obtained on the vertical seismic channel were subjected to spectral analysis. A standard 256-point Fast Fourier Transform routine with a 3-point Hamming-Tukey window (Robinson, 1967) was applied in the frequency domain in order to obtain spectral plots of the relative power versus frequency. The distances between the calibration blasts and the recording stations located within the region of high heat flow are limited to five or six km (Figs. 2 and 3). No anomalous attenuation was found. Since the maximum depth of penetration of seismic waves generated by the calibration blasts is less than 2 km in the high heat flow portion of the geothermal field, the attenuation analyses suggest that the source for the high temperature anomaly observed in the East Mesa Geothermal Field is deeper than 2 km.

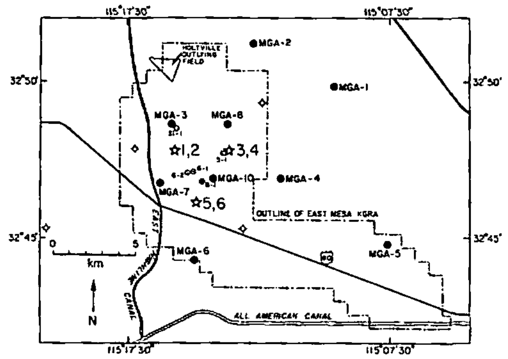

Figure 2. Location map for the June 3, 1975, East Mesa Geothermal Field refraction experiment. Calibration shot points are indicated by open stars and seismic stations by solid circles.

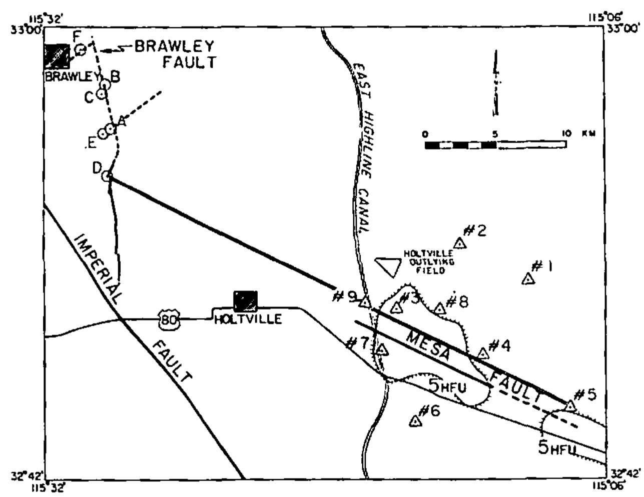

Figure 3. Location of six events of the Brawley earthquake swarm, January, 1975, [⊙] and the seismic stations [△] in the vicinity of the East Mesa Geothermal Field. The heat flow contours are from Combs and Swanberg (1978).

The Brawley earthquake swarm of January, 1975 provided an opportunity for studying attenuation characteristics in the East Mesa region for deeper subsurface layers. Swarm activity was most intense for a period of three days when 75 events in the magnitude range of 2.7 to 4.7 were located (Johnson and Hadley, 1976). These events were well recorded by the portable seismic stations operated in the vicinity of the East Mesa Geothermal Field (Fig. 3). We have examined attenuation characteristics for six of these events with differing focal mechanisms (Johnson and Hadley, 1976). Magnitudes and epicentral distances for the events ranged from 2.7 to 4.2 and 20 to 50 km, respectively. Alignment of two or more seismic stations with certain epicenters facilitated removal of the source and propagation characteristics to the nearest station. Use of internal quartz crystal oscillators for clocks in each seismograph, with routine calibration against WWV signals, as well as the low known station clock drift rates, and recording on magnetic tape allowed arrival times to be picked within ±0.01 sec.

Spectral analyses of the six Brawley events indicate that the relative attenuation of body wave amplitudes increases for the frequency range of 10 Hz and higher along the ray paths through the East Mesa Geothermal Field and also that the attenuation of the higher frequency components takes place within confined areas rather than along the entire ray path. Representative examples of the high frequency P-wave attenuation are shown in Figures 4 and 5, where the relative power as a function of frequency is depicted for the vertical component of events A and D at stations #9, #3, #4, and #5. These four recording stations lie essentially on the same ray path for each of the two events (Fig. 3). Attenuation of power for the higher frequencies is quite pronounced as the rays pass through the anomalous zone of high heat flow (Figs. 4 and 5). Furthermore, the observed high frequency attenuation is associated with the particular ray path rather than being a function of the length of the ray path. For example, stations #4 and #6 are practically equidistant from all six events. A comparison of spectra for events D and F recorded at these two stations is presented in Figure 6. The spectral contents for these two events are similar at each station even though the path lengths from event F are about twenty percent longer compared to path lengths from event D. It can also be noted from Figure 3 that ray paths from the epicenters to station #4 have a longer passage through the region of high heat flow as compared to station #6. From Figure 6, it is therefore evident that the recorded spectra at station #4 show stronger attenuation of high frequencies than does station #6 for the azimuths and epicentral distances examined.

CONCLUSIONS

Preliminary results of P-wave spectral analyses for the six events of the Brawley earthquake swarm have shown anomalous attenuation in the high frequency range. These data suggest that anomalous seismic behavior is associated with the thermal anomaly at the East Mesa Geothermal Field. However, since the epicenters are limited to a small hypocentral region and since the azimuthal coverage is restricted, the possibility exists that the observed anomalies are due to local subsurface complexities. Comparisons of the results of analyses of the Brawley events with six

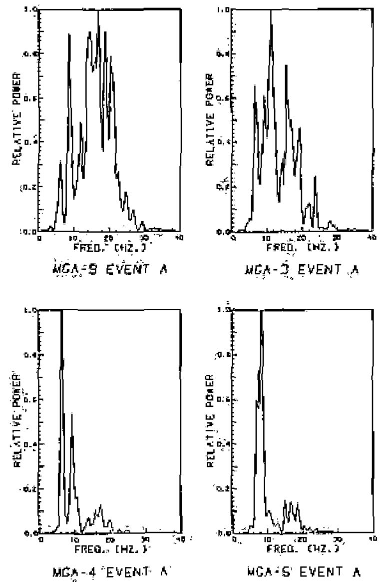

Figure 4. P-wave attenuation across the East Mesa Geothermal Field. Relative power as a function of frequency for event A at stations #9, #3, #4, and #5.

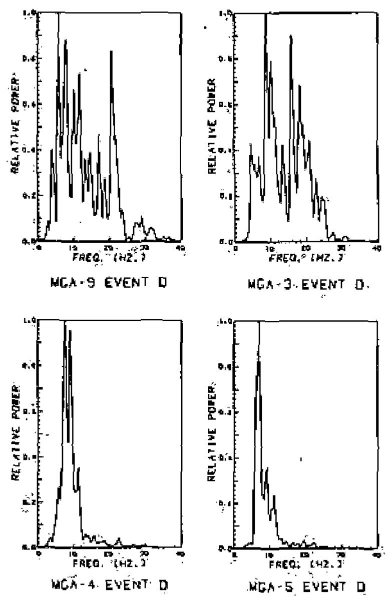

Figure 5. P-wave attenuation across the East Mesa Geothermal Field. Relative power as a function of frequency for event D at stations #9, #3, #4 and #5.

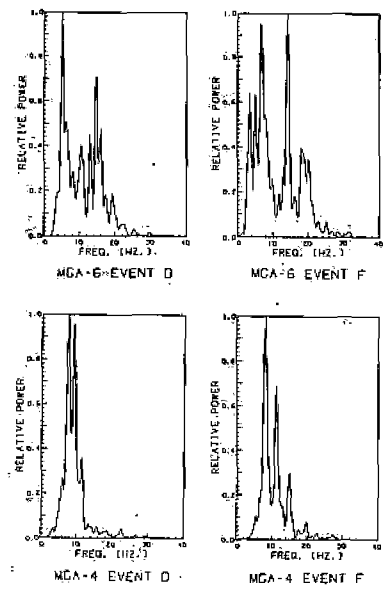

Figure 6. P-wave attenuation as a function of ray path rather than path length for events D and F at stations #6 and #4.

calibration shots detonated in the immediate vicinity of the East Mesa Geothermal Field have at least demonstrated that the cause of the anomalous behavior is not located at shallow depths, but rather should lie at depths in excess of a few kilometers. A more detailed study of the East Mesa Geothermal Field using seismic sources at varying azimuths and epicentral distances is in progress.

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